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Final report

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Warren, MI 48397-5000

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Washington, DC 20314-1000

Abstract: The U.S. Army Engineer Research and Development Center conducted a series of carefully controlled field experiments to quantify the aboveground environments created by the detonation of surface and near-surface bare-charge explosives in or on three very different soil backfills. The experiments provided blast pressure, soil stress, and impulse data for each soil type. A laboratory investigation was conducted on test specimens of each soil type remolded to approximately the same characteristics as the respective backfills. Results of the laboratory tests for each soil type were analyzed to develop a set of recommended strength and compressibility responses that in turn were fit with the simple Hybrid-Elastic-Plastic constitutive model. The model fits for each soil type were used in a series of numerical simulations using the EPIC finite element software to calculate the impulse data obtained from the field experiments. This report documents the results of those simulations and comparisons with the field data.

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Preface

The U.S. Army Engineer Research and Development Center (ERDC) was tasked by the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) and Headquarters, U.S. Corps of Engineers (USACE), to develop techniques to experimentally quantify and numerically simulate the aboveground environments produced by the detonation of surface and shallow-buried explosives on overlying structures. The research was funded by TARDEC under the Prediction of Blast, Fragments, and Soil Debris funding document in fiscal year 2010 and by USACE under the Tactical Wheeled Vehicle Survivability (TWVS) Army Technology Objective–Demonstration (ATO–D). Munira Tourner was the TARDEC TWVS ATO–D manager, Heather Kammer was the TARDEC technical point of contact for this research, and Dr. Kent T. Danielson was the ERDC TWVS work package manager. The ERDC research was conducted by staff members in the Impact and Explosion Effects Branch (IEEB), Engineering Systems and Materials Division (ESMD), Geotechnical and Structures Laboratory (GSL).

Dr. Ramon J. Moral, IEEB, conducted the numerical simulations and developed comparisons of these results with the results of the field experimental data. John Q. Ehrgott, Jr., IEEB, was the Project Engineer responsible for all experimental efforts conducted under this research effort. Drs. Charles R. Gerlach and Gordon R. Johnson of the Southwest Research Institute provided the EPIC software and simulation support. Dr. Jon E. Windham, Bevilacqua Research Corp., and Drs. Steven A. Akers and Mark D. Adley, IEEB, assisted in properly characterizing the soils for use in EPIC. This report was prepared by Dr. Moral with assistance from Tracey A. Waddell, IEEB.

During this research, Henry S. McDevitt, Jr., was Chief, IEEB; Dr. Larry N. Lynch was Chief, ESMD; Dr. William P. Grogan was Deputy Director, GSL; and Dr. David W. Pittman was Director, GSL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
bars	100	kilopascals
feet	0.3048	meters
Inches	0.0254	meters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

1 Introduction

Background

A series of five experiments was conducted with each of three soil types, i.e., wet clay, intermediate silty sand, and dry sand, with very different strength and compressibility responses. The objective of the 15 experiments was to investigate the influence of soil properties on the aboveground environment resulting from a near-surface detonation of bare, mine-shaped explosive charges (Ehrgott 2010). The purpose of these experiments was to measure aboveground airblast, reflected pressure, and soil debris loads due to a near–surface or subsurface detonation of a bare charge in a well-controlled and quantified environment. The experimental data will be used to validate the ability of numerical codes to predict these aboveground environments and, in turn, will be used in the development of protection schemes for vehicles subjected to blast effects from detonation of mines or other explosive energy sources.

Each experiment employed a 5-lb bare charge positioned either flush with the ground surface, resting on the ground surface, or buried 4 in. below the ground surface. A standoff distance of 20 in. from the top of the charge to the bottom of the piston assembly in an impulse measurement device (IMD) (Ehrgott et al. 2009) was maintained in all cases. All soil testbeds were 12 ft square by 4.5 ft deep. The pertinent experiment matrix is in Table 1. Experiments for each soil type were conducted using the IMD configurations illustrated in Figure 1. One of the experiments illustrated in the figure had the charge on the surface of the testbed, i.e., tangent surface above (TSA), and the other had the charge buried 4 in. below the surface of the testbed.

The objective of the research documented herein is to accurately simulate numerically the blast loading phenomena obtained from the experiments that involved the IMD. The impulse on the IMD was experimentally determined using the three different soils (dry sand, intermediate silty sand, and wet clay) and two different explosive charge positions (the charge resting on the soil surface and the top of charge buried 4 in. below the soil surface). Two numerical simulations were performed for three different soils

Table 1. IMD experiment matrix.

Test Number	Charge Mass C-4 lb	Soil Type	Explosive Charge Position	Depth of Burial in.	Target Standoff in.	Test Configuration
BM-I-04	5	SM	TSA	-	20	IMD
BM-I-05	5	SM	BURIED	4	20	IMD
BM-C-04	5	CL	TSA	-	20	IMD
BM-C-05	5	CL	BURIED	4	20	IMD
BM-S-04	5	SP	TSA	-	20	IMD
BM-S-05	5	SP	BURIED	4	20	IMD

Notes: Soil types are CL for lean clay, SM for silty sand, and SP for poorly graded sand per the Unified Soil Classification System.

Charge Positions: TSA = tangent surface above.

Depth of burial is measured from top of charge to ground surface.

Target standoff is measured from top of charge to bottom of IMD or centerline of side-on overpressure gages.

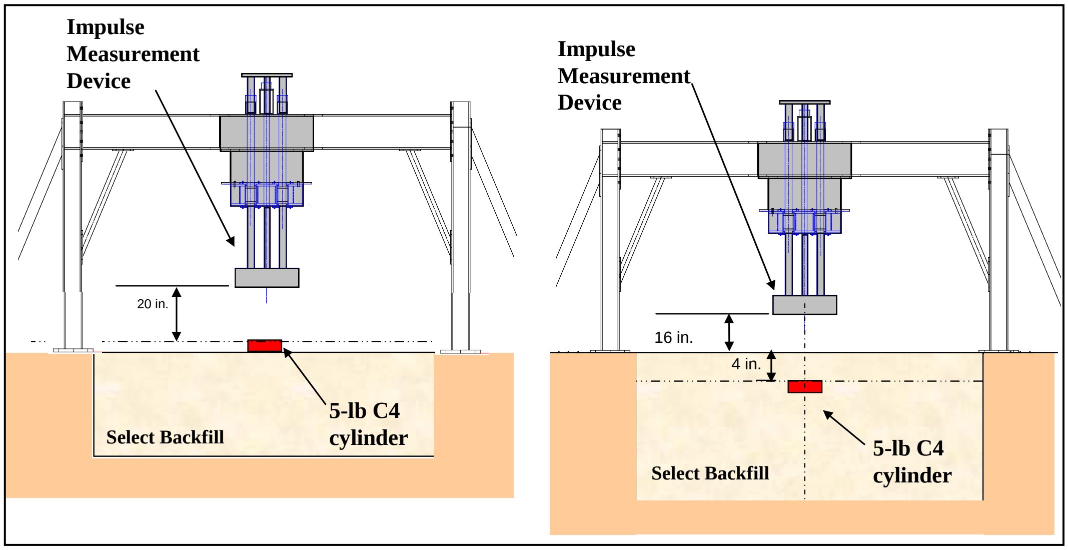

Figure 1. Example layouts for the IMD experiments.

for a total of six different simulations per soil. The first two configurations are the buried and resting positions. Additionally, in the simulations, a third configuration with the top of the charge flush with the soil surface was used. The success of this work relied on the unique capabilities of the EPIC software package (Gerlach 2009) and the experience within the U.S. Army Engineer Research and Development Center in fitting soil properties with the Hybrid Elastic Plastic (HEP) material model (Zimmerman et al. 1987) for modeling applications involving soil response to explosive charges.

Purpose and scope

The purpose of this report is to document the results of numerical simulations of field experiments conducted to measure aboveground impulse loads from detonation of explosive charge in three different positions (surface laid, top surface flush, and buried) within three very different soil types. Chapter 2 contains an overview of the EPIC and SABER Lagrangian codes and the HEP constitutive model used to mathematically describe the soil responses in both EPIC and SABER. Chapter 3 describes the results of the EPIC numerical simulations of the IMD field experiments and compares the impulse values obtained from the simulations and experiments. Chapter 4 contains a summary and conclusions from the research and recommendations for future research.

2 EPIC, SABER, and the HEP Model

When a buried mine or other explosive energy source is detonated near a structure, some very complex responses and interactions occur. The explosive-detonation products develop high pressures and expand to volumes hundreds of times greater than their initial volumes, the air is compressed by the explosive shock to a small fraction of its initial volume, and the soil experiences large distortions as it goes from very high pressures to relatively low pressures as it is ejected from its initial position. Furthermore, the resulting intermixture of these materials produces some very complex interfaces. In addition, metallic (or sometimes nonmetallic) components and/or structures can be present. If the mine or other explosive energy source has a metal case, failure and fragmentation of the case may occur, sending the fragments through the mixture of soil, air, and detonation products. Finally, if a structure is within the affected region, that structure is subjected to intense impulsive loads from the detonation products, the airblast, the dispersed soil, and/or the high-velocity fragments.

The EPIC Lagrangian code was developed and later modified (Gerlach and Johnson 2008 and 2009) to calculate these complex interactions. The EPIC software has two unique features that make it attractive for use in any kind of soil-air-structure-explosive interaction simulations. First, EPIC has the ability to convert conventional meshed elements into generalized particle algorithm (GPA) particles (Johnson et al. 2006). This conversion allows large deformations to occur in the simulation without remeshing or element deletion. Remeshing is a time-consuming and fault-prone process of redistributing the elements and nodes in a simulation once the deformations in an initial element mesh reach a point at which the mesh contains too many numerically unstable, or meaningless, elements. This method of dealing with large deformations provides a way to preserve the mass of the mesh throughout a simulation. However, there are no guarantees that a deformed geometry can be remeshed; hence, a simulation may not run to completion.

In the element-deletion method, elements in a mesh are removed when they become too distorted to provide good results or when the material model makes the element too weak to contribute to the simulation, which leads to the former condition. By avoiding the remesh step, the deletion method assures that a simulation can run to completion. The problem that element deletion presents is that the mass of the mesh is not conserved throughout the simulation. EPIC does provide a method for conserving mass during deletion, but this methodology does not properly model soil ejecta from a buried explosion impacting the IMD. In the case of a buried munition analysis, this deficiency is not acceptable, as highly distorted debris impacting the target is an important component of the problem.

By the conversion of distorted elements into GPA particles, remeshing is avoided, and the mass of the particles is conserved throughout a simulation. The GPA particles can become “dead” materials (unable to support deviatoric stresses) and still transfer momentum and transient pressure waves from one simulation entity to another; i.e., failed soil particles can still impact the bottom of a vehicle and provide an impulse.

Regardless of the capabilities of the finite element software in question, without proper material models and accurate material properties, acceptable simulations of any given phenomena are nearly impossible. The Hybrid-Elastic-Plastic (HEP) model was used to describe the behavior of soils in EPIC. The HEP material models in EPIC were developed to simulate blast-induced geologic material behaviors (Akers, Adley, and Cargile 1995 and Zimmerman et al. 1987), specifically for calculating ground shock from conventional weapons. A simple pressure-dependent, deviatoric, failure-theory coupling was chosen for the models over a rigorous deviatoric-volumetric coupling, to more easily implement highly sophisticated pressure-volume models. Therefore, the HEP model cannot simulate shear-induced dilation. The advanced equations-of-state for the volumetric response are thought to be more important in high-pressure applications.

The model accurately replicates the complex stress-strain behavior of ductile geologic materials and is fit to typical laboratory high-pressure mechanical property test results. The HEP model uses a nonassociative, elastic-plastic, exponential failure surface (Figure 2), a constant load and constant unload Poisson's ratio (Figure 2), and a robust pressure-volume algorithm employing multiple regions of nonlinear load-unload-reload logic (Figure 3). The exponential failure surface is a two-invariant, pressure-dependent surface that is fit to quasi–static triaxial compression failure data. Several material fits also use more complex Poisson’s ratio schemes and additional pressure-volume subregions.

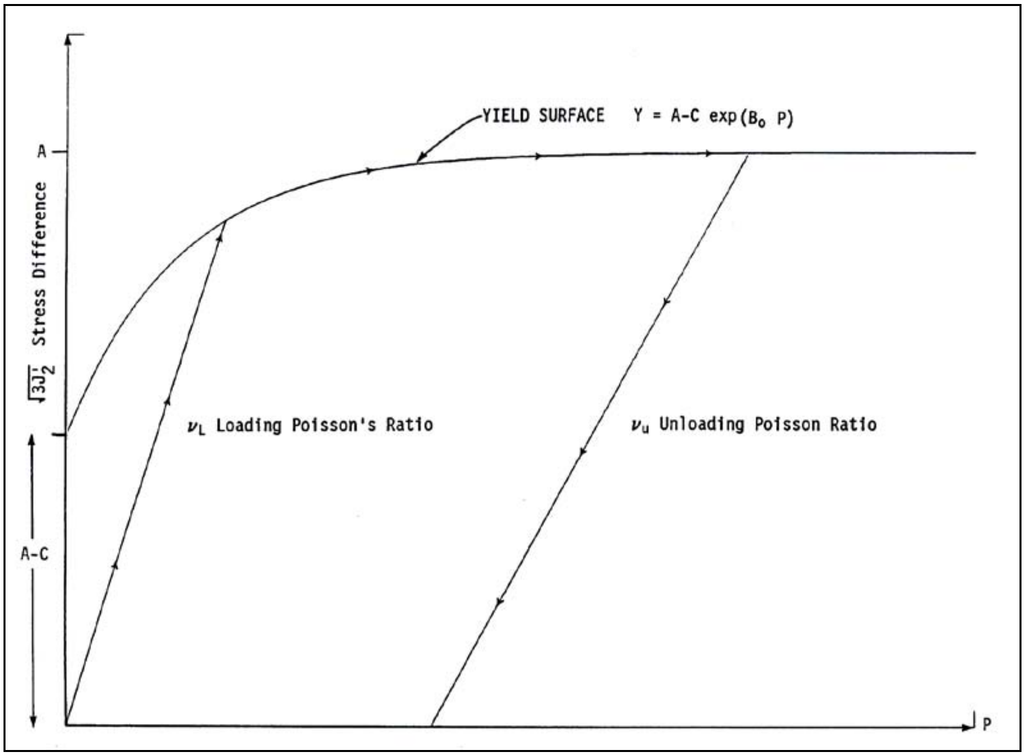

Figure 2. Model for simple HEP deviatoric behavior.

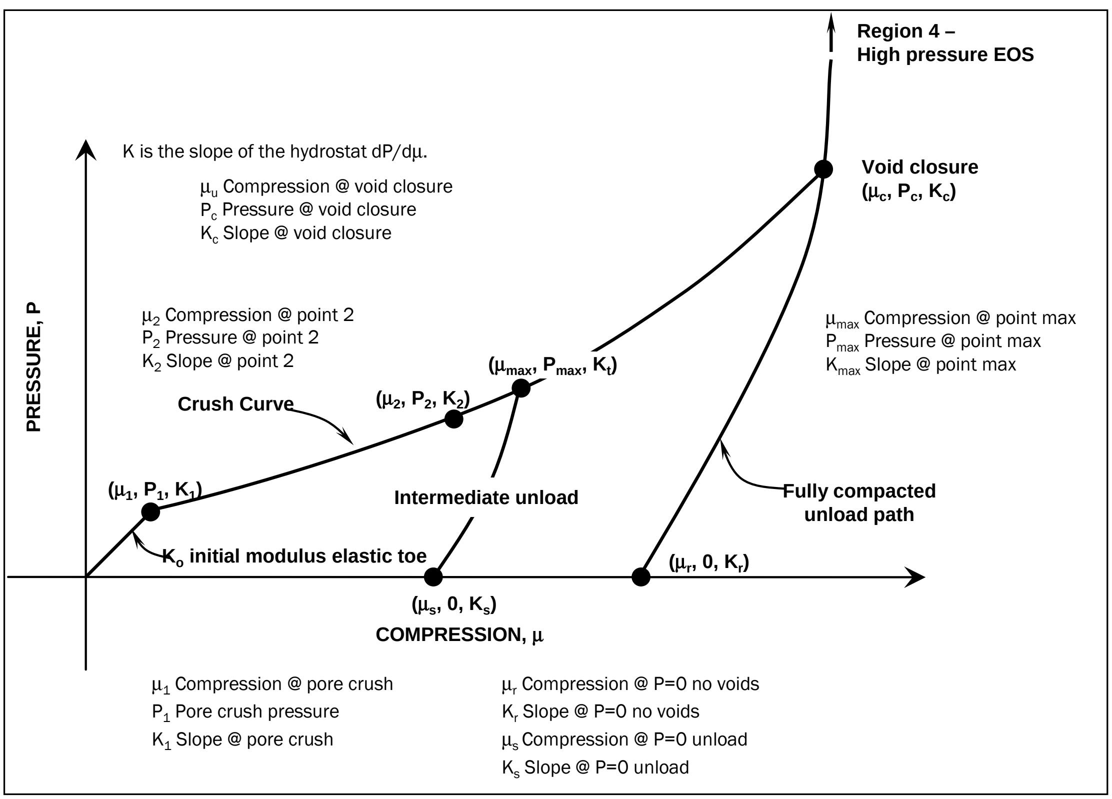

Figure 3. Pressure-compression relation for the HEP model.

The HEP material models were originally implemented into the SABER code. SABER-1D (Zimmerman, Shimano, and Ito 1992) is a first-principle, one-dimensional (1-D), spherically symmetric, Lagrangian finite-element code developed to calculate ground shock range-to-effect from the detonation of a fully buried conventional weapon. Explosive sources are mathematically represented by the Jones-Wilkins-Lee (JWL) equation of state (EOS) for 12 conventional explosives (Dobratz and Crawford 1985) commonly used by the Department of Defense community.

The original model fits in SABER were validated against a number of scaled explosive field tests. The validation methodology was to (1) conduct well-controlled ground-shock tests in which soil backfills were carefully placed to tightly controlled and quantified density and water content specifications, and redundant soil stress and particle velocity measurements were made versus range, (2) conduct uniaxial strain (UX) and triaxial compression (TXC) mechanical property tests on specimens of the soil backfield remolded to field-measured densities and water contents, (3) analyze these mechanical property data to determine recommended UX stress-strain, pressure-volumetric, and stress-path relations and a TXC failure relation, (4) fit the HEP model to the recommended properties, (5) implement these models into the SABER finite-element code and numerically simulate the experiments, and (6) compare the ground shock measurements with the calculated results to validate the HEP models and the overall methodology.

The HEP constitutive model library in SABER was later included in the production versions of the EPIC code (Johnson et al. 2006). This library of HEP models is readily accessible in EPIC and consists of 26 fits to various geomaterials (dry, partially-, and fully-saturated) including concretes, sands, clays, silts, crushed rock, and limestone.

The process for obtaining the HEP coefficients needed to simulate the IMD experiments in EPIC began at the test site. Samples of the soils used in the IMD experiments were tested at ERDC. Recommended soil properties were then developed using the methods described by Jackson (1969). These recommended IMD testbed materials include a 5.6 %-air-filled-voids wet clay (Ehrgott et al. 2010c), a 10.8%-air-filled-voids intermediate silty sand (Ehrgott et al. 2010b), and a 29.8%-air-filled-voids dry sand (Ehrgott et al. 2010a). The approach to develop the HEP model fits to the three IMD testbed materials was the same as that used in the validation methodology except for the details in the last two steps; i.e., the SABER driver simulated the laboratory mechanical property responses and the SABER-generated material response relations were compared with the recommended mechanical properties for each soil type to validate the SABER HEP model accuracy. The HEP model fits were then implemented into EPIC.

Figures 4 and 5 show the pressure-volumetric relations and failure surfaces, respectively, for the HEP library dry sand in SABER (DEMODRY1) and the HEP fit to the dry sand used in the IMD experiment. Figures 6 and 7 are plots of the pressure-volumetric relations and failure surfaces, respectively, for the HEP library intermediate silty sand in SABER (ISOIL1) and the HEP fit to the intermediate soil used in the IMD experiment. Figures 8 and 9 are the same relations but are for the HEP library clay in SABER (WCLAY1) and the HEP fit to the wet clay used for the IMD experiments.

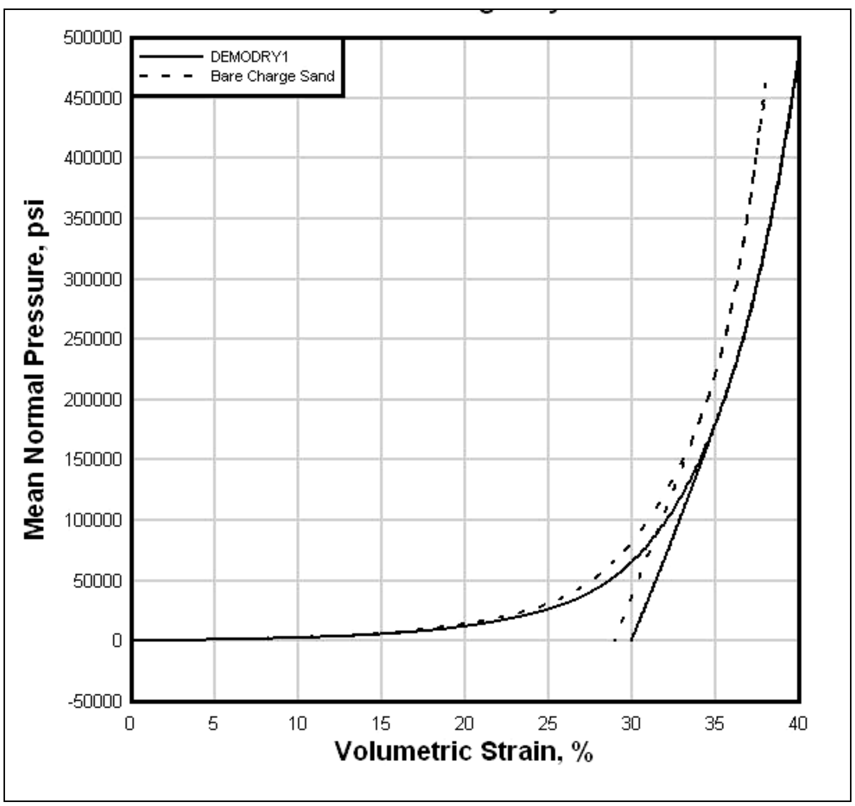

Figure 4. HEP pressure-volumetric relations for DEMODRY1 and IMD dry sand

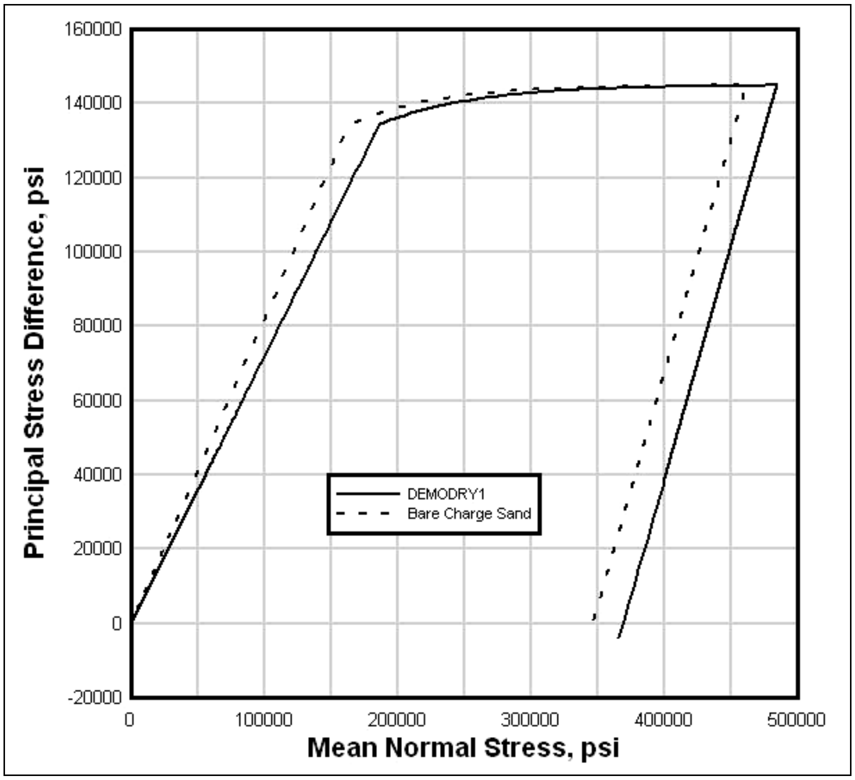

Figure 5. HEP failure relation for DEMODRY1 and IMD dry sand.

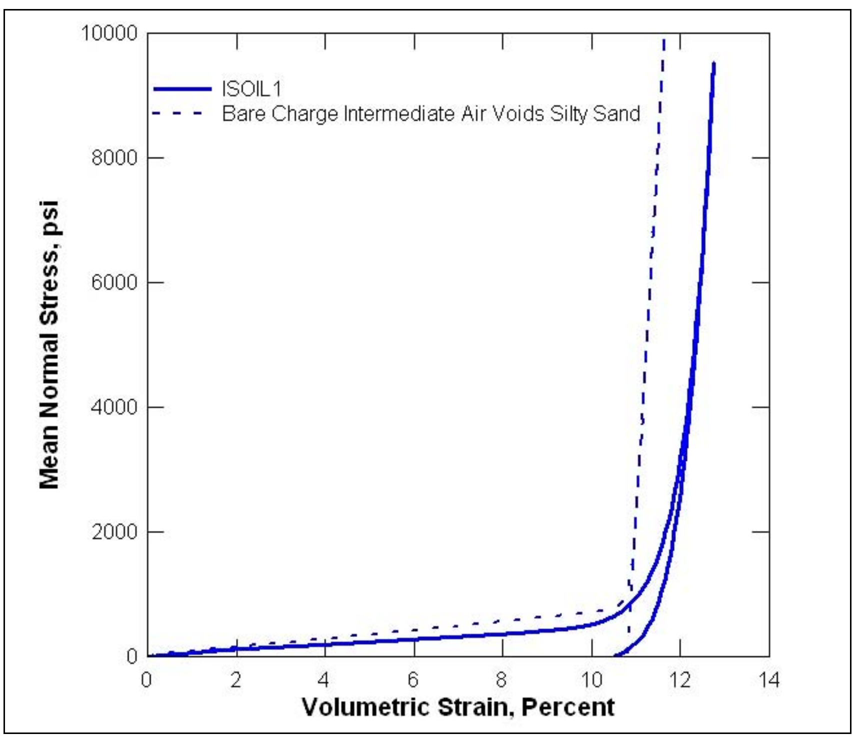

Figure 6. HEP pressure-volumetric relations for ISOIL1
and IMD intermediate air voids silty sand.

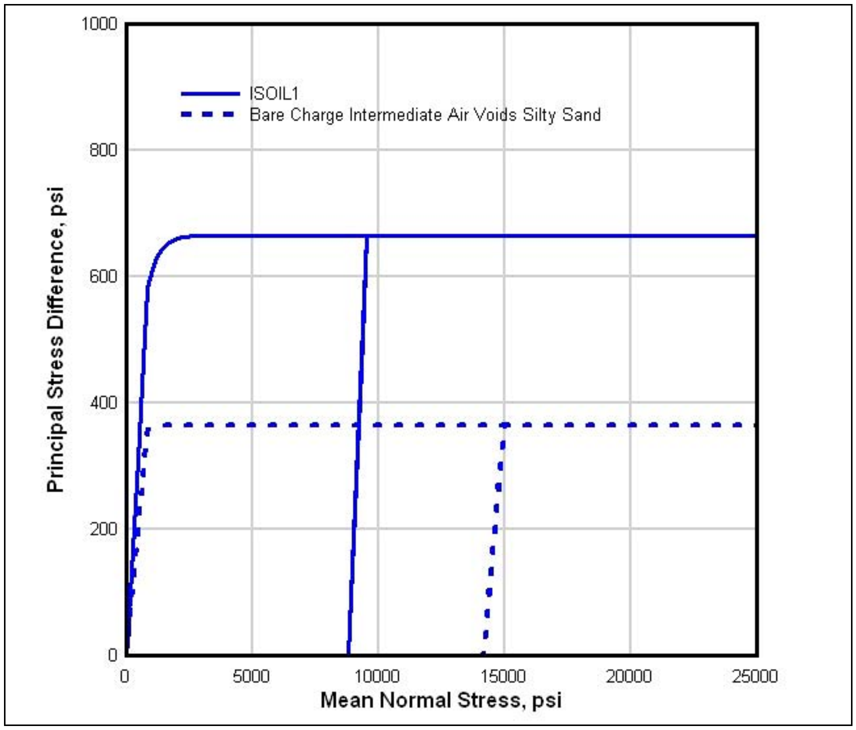

Figure 7. HEP failure relations for ISOIL1 and IMD intermediate air voids silty sand.

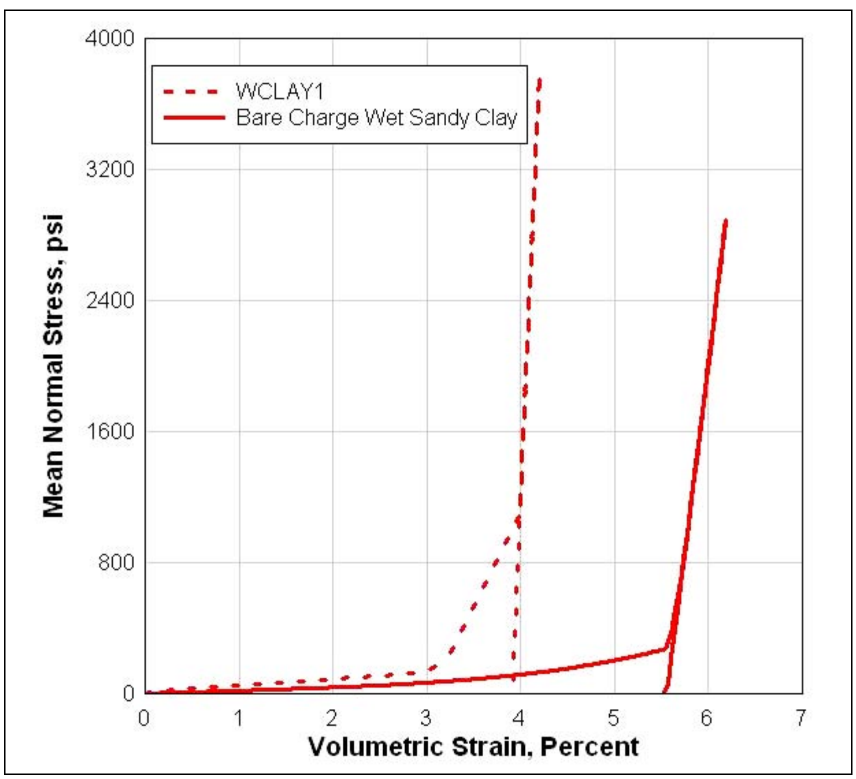

Figure 8. HEP pressure-volumetric relations for WCLAY1 and IMD wet clay.

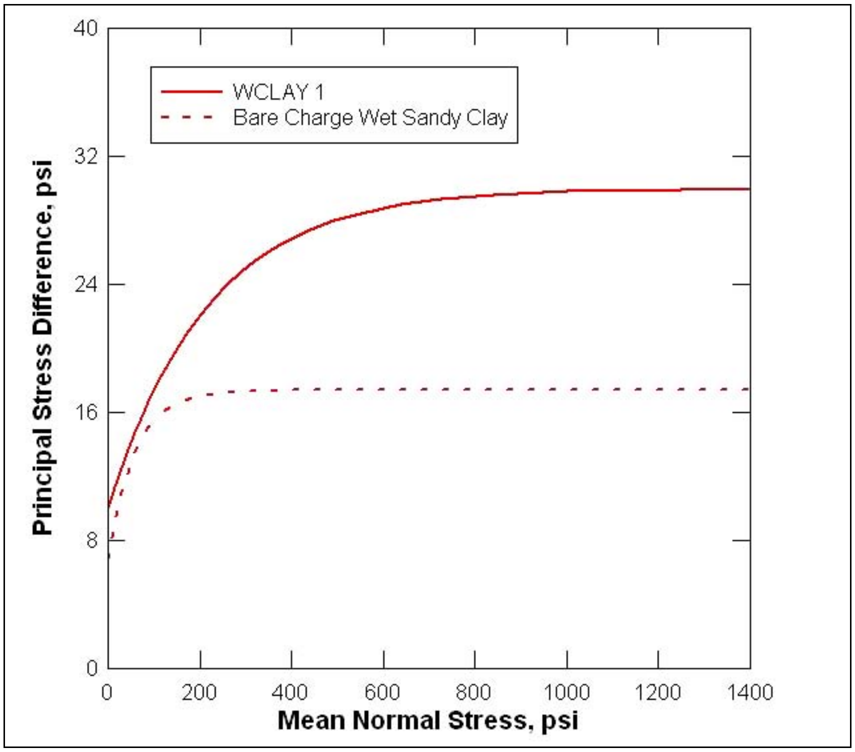

Figure 9. HEP failure relations for WCLAY1 and IMD wet clay.

The differences in the mechanical responses of the library materials and the soils from the experiments show the need to fit soil properties as accurately as possible in order to conduct numerical simulations that attain the most accurate results possible. However, it can be seen that the library materials offer responses that are very useful for any preliminary or pre-experiment simulations.

A 1-D spherical ground shock calculation was conducted with both SABER and EPIC for the dry sand backfill case, and the resulting radial stress and radial particle velocity output are compared in Figures 10 and 11, respectively. The calculations consisted of a 2.3-kg (5-lb) sphere of C4 explosive detonated in a spherical space of dry sand with radial stress and radial particle velocity output at the 0.84-, 1.06-, 1.17-, 1.31-, and 1.42-m ranges (2.75, 3.47, 3.84, 4.30, and 4.66 ft). The results of the SABER and EPIC calculations indicate that the fidelity of HEP models is maintained in the EPIC implementation and installation. Similar results were obtained for the intermediate silty sand and wet clay HEP model fits.

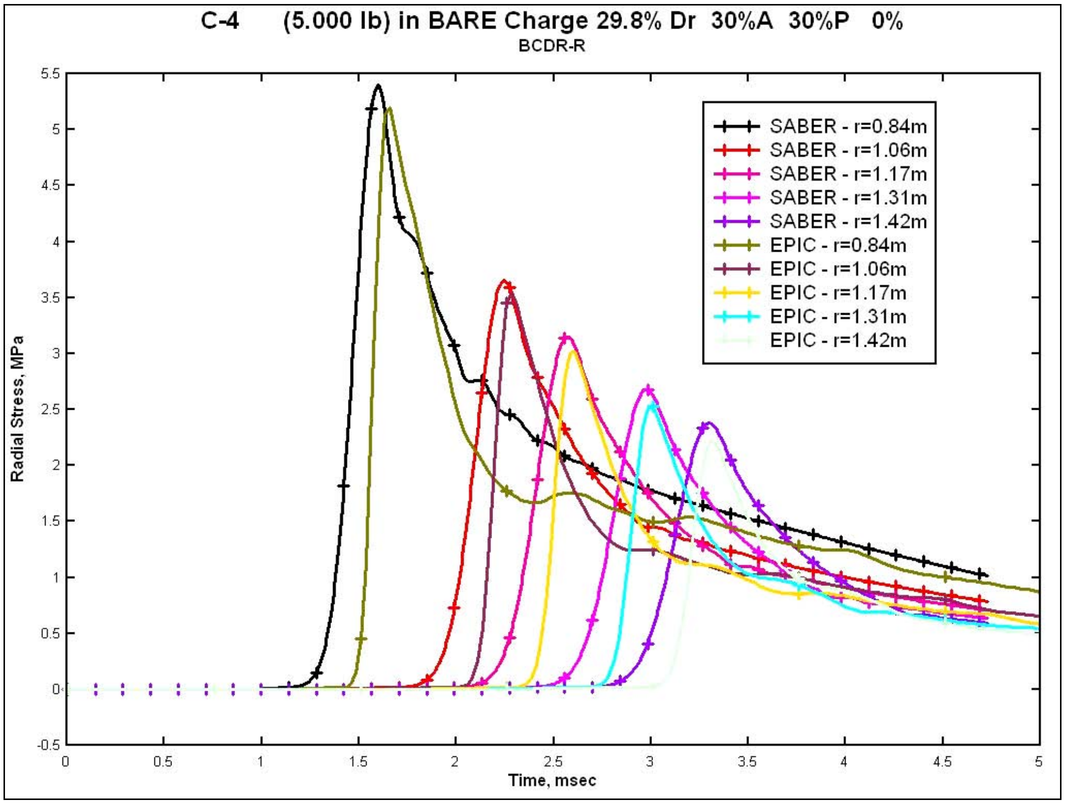

Figure 10. Radial stress vs. time for EPIC-SABER spherical model comparison.

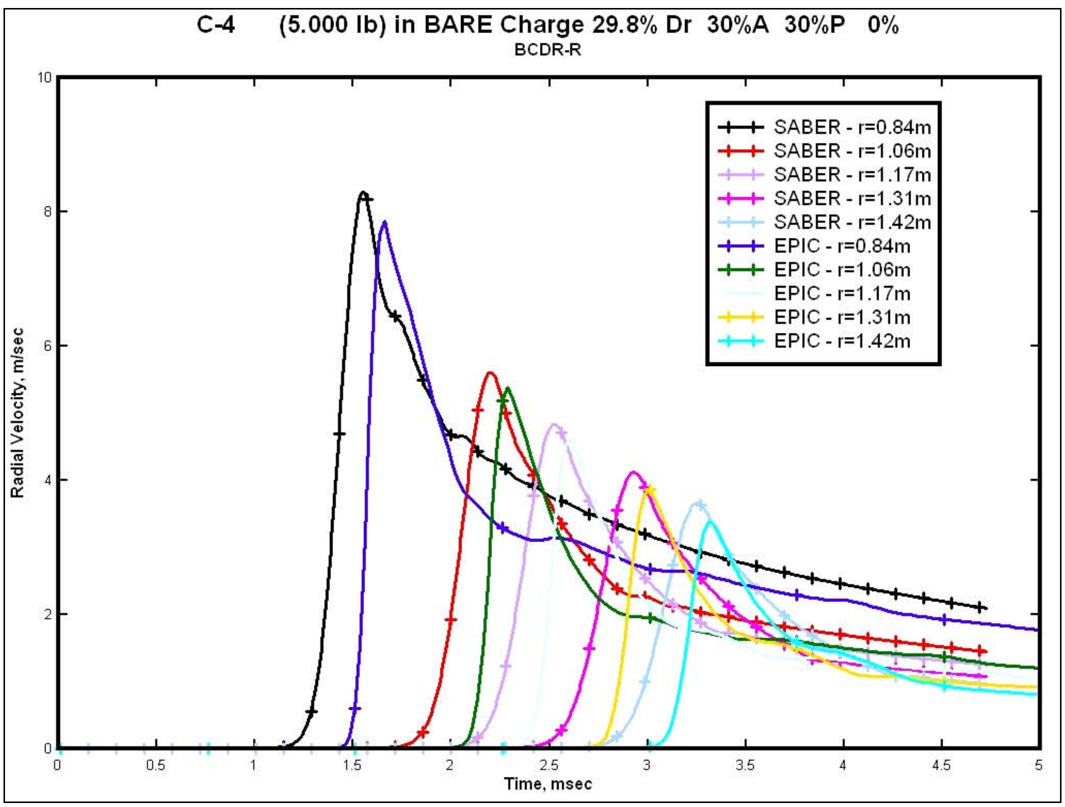

Figure 11. Radial velocity vs. time for EPIC-SABER spherical model comparison.

3 Simulations of IMD Experiments

The impulse measurement device (IMD) is an apparatus used to measure the impulse from the detonation of a buried charge. A charge is placed under the IMD; the charge is then detonated, and the vertical travel of the IMD's piston is measured. From these data, the accelerations, velocities, and positions versus time for the IMD are acquired. Figure 12 illustrates the simplifications made to the experimental set up (Figure 1) for the simulation effort. The numerical models in these simulations have only four components: soil, IMD, air, and explosive charge.

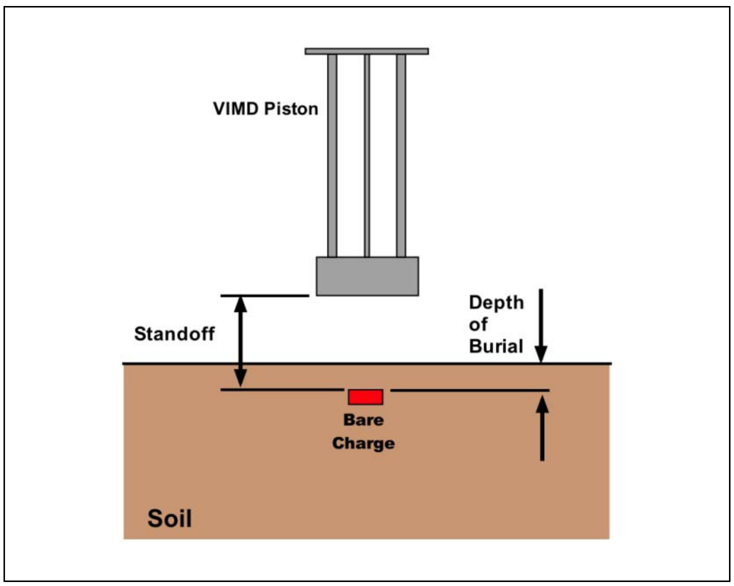

Figure 12. Illustration of components included in numerical simulations.

The primary variables explored in the IMD experiments were soil type and soil confinement. The impulse generated by the detonations in three soils was measured. The explosive charge was placed in one of two different soil confinement configurations, i.e. either buried 4 in. below the surface or sitting on the soil surface. Although no IMD experiments were conducted with the top of the charge flush with the soil surface, numerical simulations were conducted for this case. The depth of burial (DOB) is measured from the soil surface to the top surface of the charge. The charge used for the experiments was a cylinder of C-4 explosive with a 6.9-in. diameter and a 2.3-in. height. The standoff from the top of the charge to the IMD's impact plate for all impulse tests was 20 in. Table 2 summarizes the values of total impulse obtained from the experiments.

Table 2. Peak impulse values from IMD experiments (from Ehrgott 2010).

Material	Experimentally Measured Impulse, N·s		
	Buried (4-in. DOB)	Flush (0-in. DOB)	On Top (-2.3-in. DOB)
Dry sand	7740	N/A	2753
Intermediate silty sand	8400	N/A	2424
Wet clay	11650	N/A	2891

Multiple simulations were performed for each experimental case, using two different mesh densities and the different soil model fits. In the first set of simulations, the models were evaluated using the HEP library materials in EPIC that were the closest match to the soils used in the experiments. In the second set of simulations, HEP fits determined experimentally for the materials used in the actual experiments were used in the models. A set of simulations is one model per experimental setup, or nine models per set. Figures 13–15 show the initial meshes for the three charge arrangements in the soil.

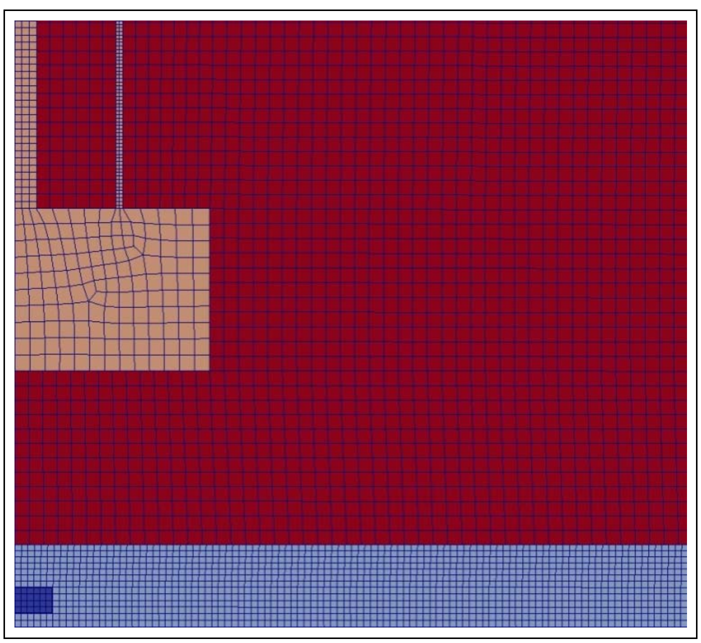

Figure 13. Buried charge.

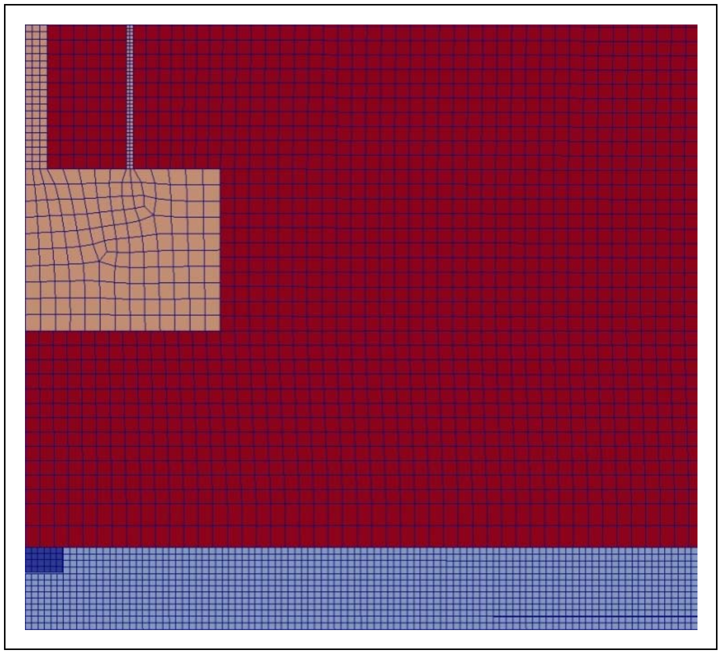

Figure 14. Top of charge tangent to soil surface.

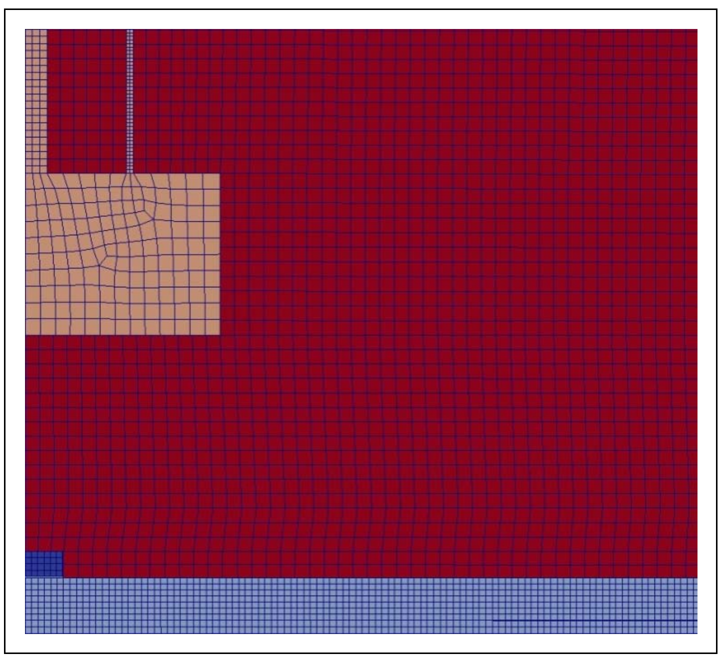

Figure 15. Charge lying on soil surface.

The meshes are axisymmetric representations of the actual experimental setups. The left edge of each figure is at the center of the charge, or r = 0, and defines the z-axis of revolution. The axisymmetric models were chosen over three-dimensional models to save computation time. All simulation models consisted of four materials: HEP soil model, described earlier; 4340 steel for the IMD (Johnson and Cook 1985); C-4 for the charge

(Dobratz and Crawford 1985); and air as an ideal gas. Figure 16 presents plots of the impulse time-histories for the first two simulation sets for the buried charge configuration.

The most obvious observation from Figure 16 is the significant differences between impulse simulations with the HEP library materials and those performed with HEP fits to the experimental backfill soils. The library intermediate silty sand and wet clay have the largest peak impulses. The simulations with the HEP library materials and the experimental results show a similar trend. The greatest impulse magnitude is with wet clay materials, with the intermediate soil and dry sand second and third in magnitude, respectively. The simulations using the experimental material fits show little differences between the wet clay and intermediate soil impulse values.

Figure 17 is a plot of the simulated results for the charge buried with its top surface flush with the soil surface. Unlike the buried charge case, the results in these simulations indicate little difference between the library

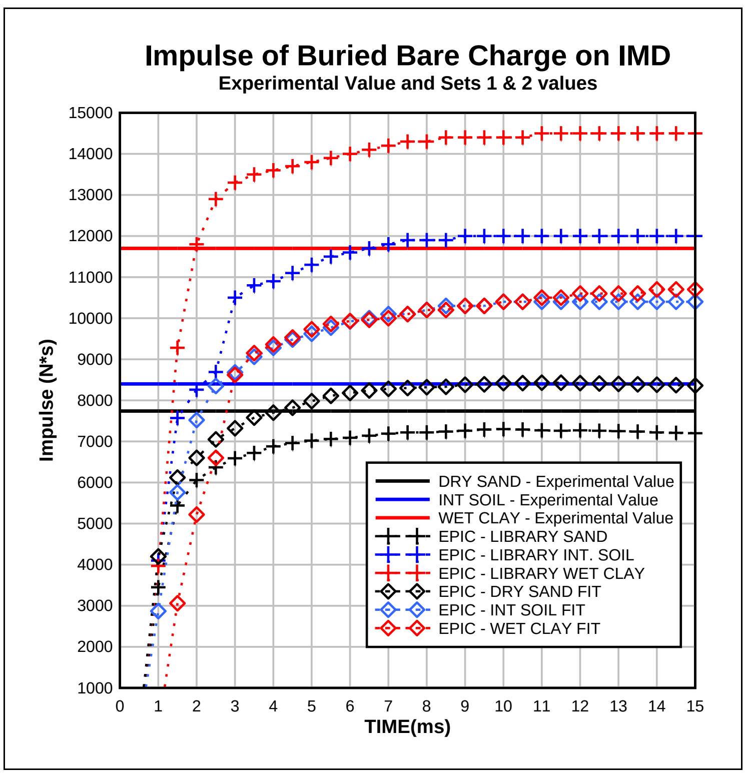

Figure 16. Calculated impulse for buried bare charges of Simulation Sets 1 and 2.

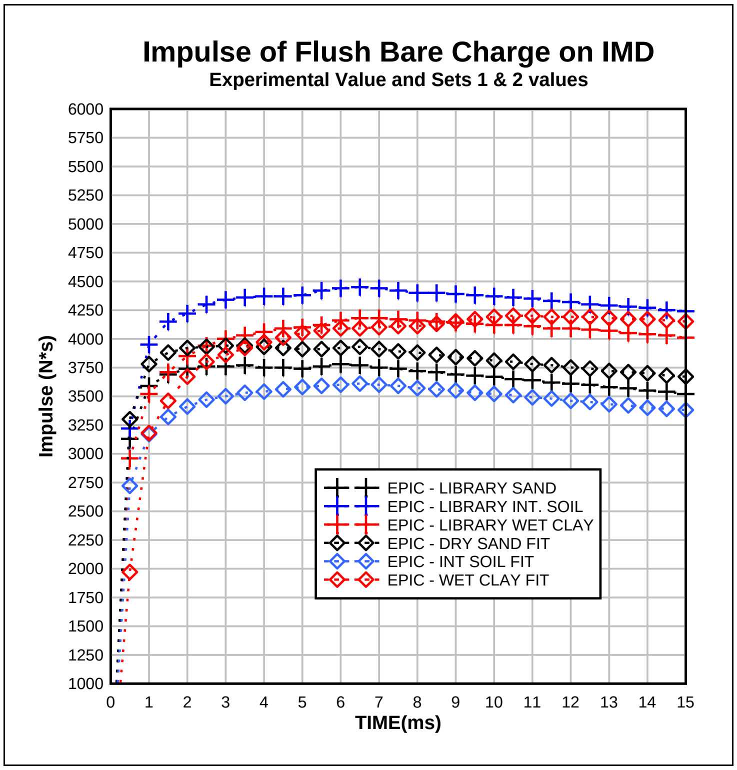

Figure 17. Calculated impulse for flush bare charges of Simulation Sets 1 and 2.

and actual material fits for the dry sand and wet clay. The results for the intermediate soils are very different and contradict the trend seen in the experimental data for the buried charge (Figure 16).

In Figure 18, the simulation and experimental impulse plots for the charge sitting on the ground surface are shown. The simulation results for the dry sand and wet clay cases have much lower peak impulse values than the experimental values. The results from the intermediate soil simulations are only slightly lower than the experimental results. The spread of peak impulse values between the HEP library and the actual material fits is small compared to the spread in the experimental values.

To further explore the capabilities of EPIC, two more sets of simulations were performed. The simulations in Sets 3 and 4 are the same as in Sets 1 and 2, respectively, except that the mesh size was halved for the soil, explosive, and air. Figure 19 shows the mesh for the charge in the buried position for Simulation Sets 3 and 4. Because of the larger number of elements, the calculation run times for Sets 3 and 4 simulations were in “days.” Simulation Sets 1 and 2 ran in hours.

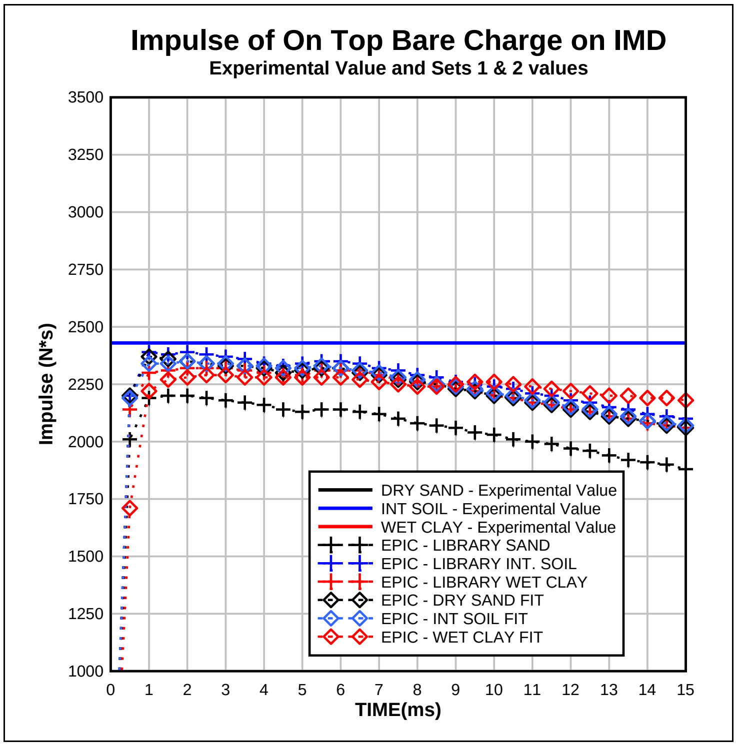

Figure 18. Calculated impulse for surface bare charges of Simulation Sets 1 and 2.

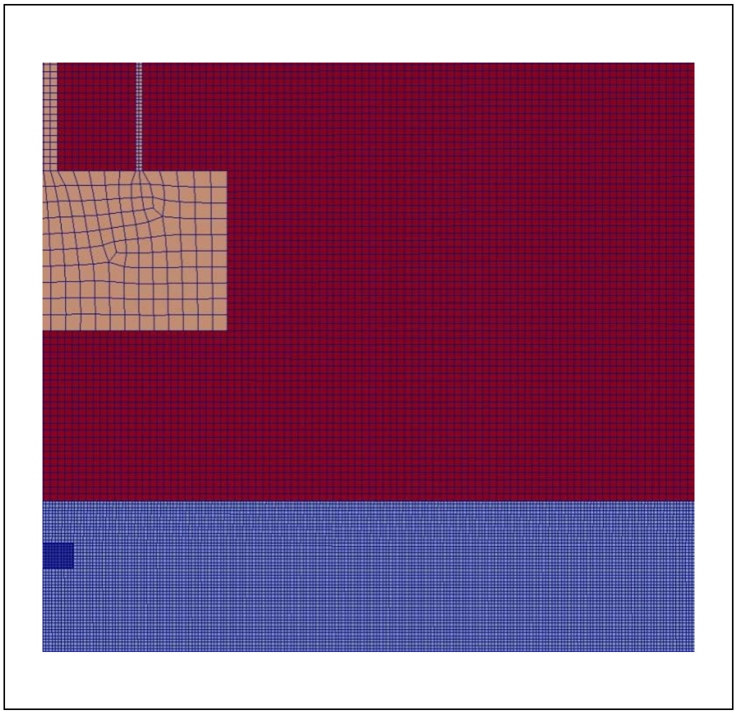

Figure 19. Refined mesh for buried charge in Simulation Sets 3 and 4.

Figure 20 shows Sets 3 and 4 results for the buried charge. There are two significant differences between these results and those in Simulation Sets 1 and 2 (Figure 16). First, the differences between HEP library material results and the actual material HEP fit results are smaller. Also, the results using the actual HEP fit materials follow the expected trends in the peak impulses as in the experiments.

Figure 21 presents the results for Sets 3 and 4 simulations for the charge buried with its top flush with the soil surface. The refinement of the mesh has improved the results again over Sets 1 and 2 results (Figure 17). One trend worth noting is that the magnitude of the simulated impulses increased with increased mesh density.

Figure 22 shows the plots for Sets 3 and 4 simulations for the charge sitting on soil surface. Once again, the increase in mesh density caused an increase in the calculated impulse (see Figure 18). In this case, the increase places the simulated results within the range of the experimentally determined peak impulse values. The only result of concern is that the HEP library intermediate soil yielded unexpectedly high peak impulse values.

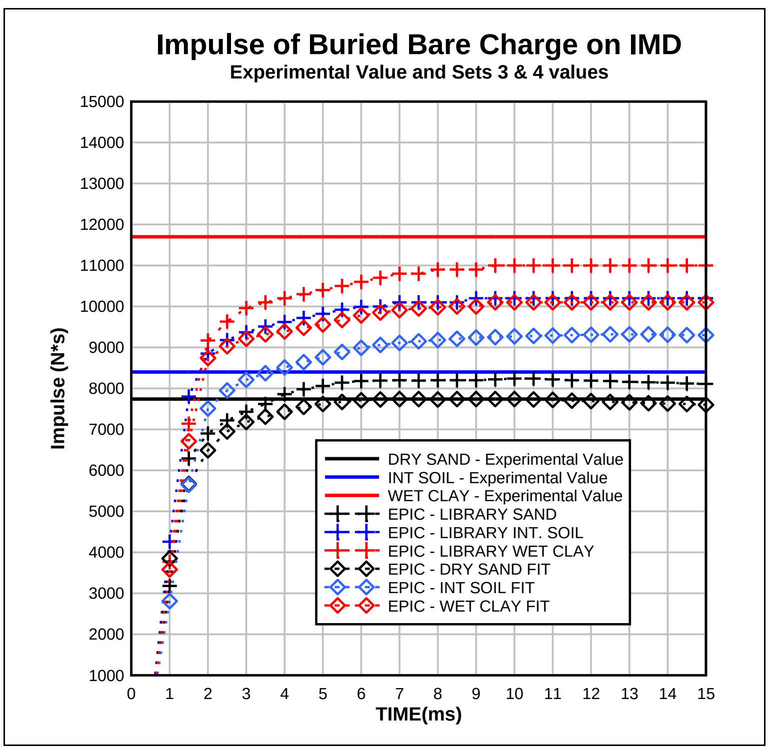

Figure 20. Calculated impulse for buried bare charges of Simulation Sets 3 and 4.

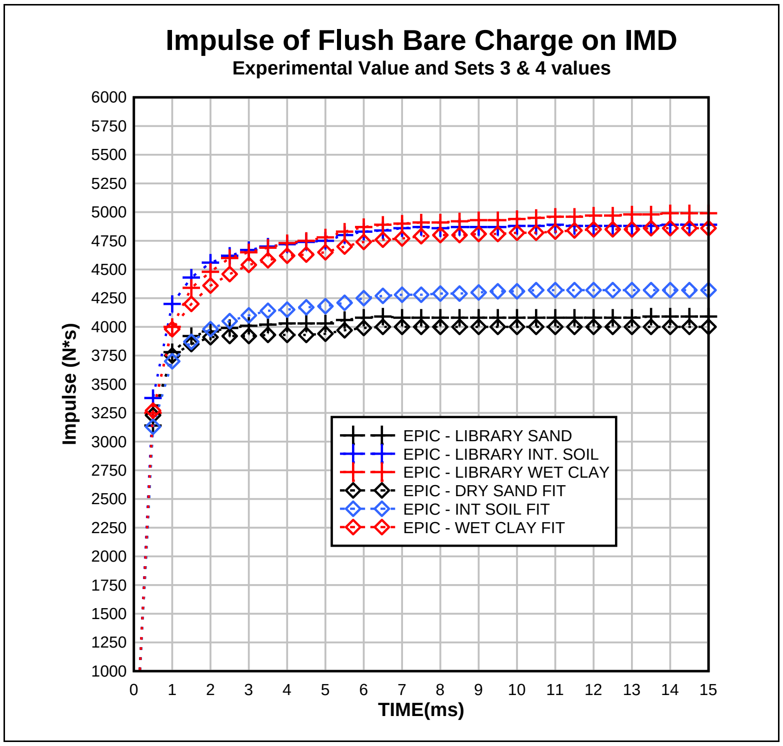

Figure 21. Calculated impulse for flush bare charges of Simulation Sets 3 and 4.

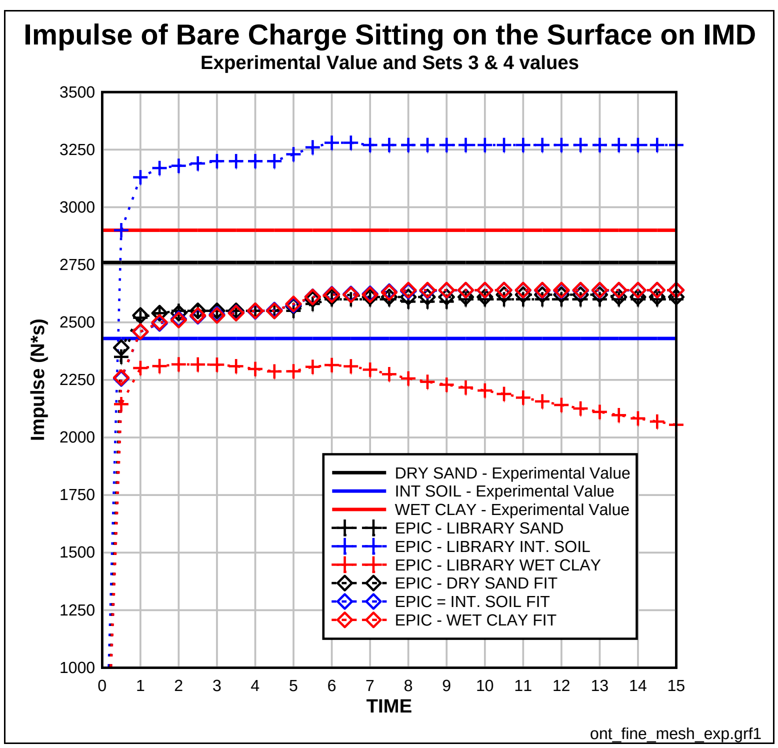

Figure 22. Calculated impulse for surface bare charges of Simulation Sets 3 and 4.

4 Summary, Conclusions, and Recommendations

The soil-airblast interaction experiments performed with the IMD were simulated using EPIC finite element software. Simulations were performed for three charge arrangements and three soil types, or nine experiments. The simulations were divided into four sets. Each set contained one simulation for each experiment performed with the IMD. In two of the sets, HEP library materials from EPIC that were closest to the mechanical responses of the experimental soils were used in the simulations. In the remaining two sets, HEP fits generated from mechanical property data for the actual experiment soils were used. In Sets 1 and 2, a reasonably dense mesh was used for the soil, explosive, and air in the simulations. In Sets 3 and 4, a mesh with double-node density was used. The material choices and mesh densities have significant effects on calculated solutions. The denser mesh in the last two sets of simulations tended to lower the peak impulse for the buried charge and raise the peak impulses for the other flush and surface charges.

A higher element density means more, smaller GPA particles after conversion in EPIC. For the buried charge calculation, the smaller particles translated into lower peak impulse values. At the time of this writing, the two causes that seem likely are (a) the smaller GPA particles of the denser mesh do not have the same momentum as the particles of the coarser mesh (with respect to the direction of the momentum vectors) and (b) somehow, the denser mesh allows the explosive gases to escape the confinement of the soil more efficiently. More work and more sophisticated analysis/visualization techniques need to be applied to the output from EPIC to better understand this phenomenon.

The increased calculated peak impulse values for denser meshes for the flush and surface simulations seem to contradict the findings in the previous paragraph. In these simulations, the soil material is compacted more than it is expanded and tossed into the air. Soils can withstand much more compressive loading than tensile loading. In the HEP material model, tension and compression of the soil follow two completely different load paths in order to reflect this behavior. The increase in peak impulse values is a reflection of the mesh's better capturing the mechanical responses of the soils.

In general, the EPIC finite element models were able to capture the trends in the experimental data when a dense mesh and a HEP fit to the exact experiment material were used. Additional study needs to be performed on the topic of mesh grading techniques versus accuracy for the types of simulations performed in this research. With the dense mesh and HEP fit soil, the simulation took days to complete. This process can be accelerated if a mesh grading technique that lowers the size of the model (while keeping accuracy) can be developed for soil-air-explosive interaction problems.

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14. ABSTRACT

The U.S. Army Engineer Research and Development Center conducted a series of carefully controlled field experiments to quantify the aboveground environments created by the detonation of surface and near-surface bare-charge explosives in or on three very different soil backfills. The experiments provided blast pressure, soil stress, and impulse data for each soil type. A laboratory investigation was conducted on test specimens of each soil type remolded to approximately the same characteristics as the respective backfills. Results of the laboratory tests for each soil type were analyzed to develop a set of recommended strength and compressibility responses that in turn were fit with the simple Hybrid-Elastic-Plastic constitutive model. The model fits for each soil type were used in a series of numerical simulations using the EPIC finite element software to calculate the impulse data obtained from the field experiments. This report documents the results of those simulations and comparisons with the field data.

15. SUBJECT TERMS

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EPIC code	Finite element	Impulse
Explosive experiments	HEP model	Meshless particles

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